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# EFFECTS OF OIL ON BIOLOGICAL WASTE TREATMENT

George Henry Neill, et al

Texas University
Austin, Texas

1970

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Technical Report to the
FEDERAL WATER POLLUTION CONTROL ADMINISTRATION
EHE-70-03
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# *Effects of Oil on Biological Waste Treatment*

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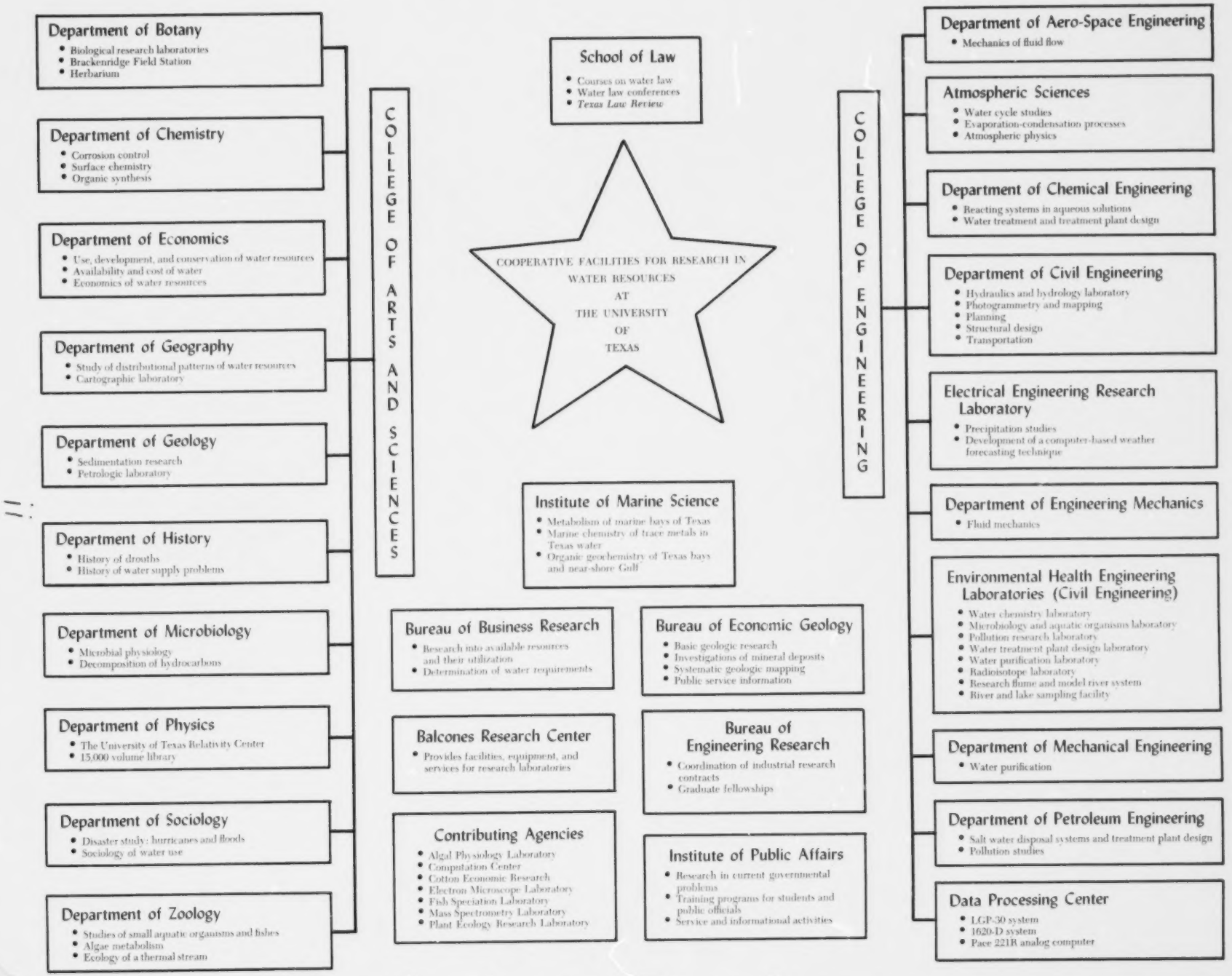
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The University of Texas at Austin
CENTER FOR RESEARCH IN WATER RESOURCES
Environmental Health Engineering Research Laboratory
Department of Civil Engineering

# EFFECTS OF OIL ON BIOLOGICAL WASTE TREATMENT

George Henry Neill, Research Assistant
Earnest F. Gloyna, Project Director

Technical Report to the
Federal Water Pollution Control Administration
5T1-WP-183-02



EHE-70-03
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## SUMMARY

Biological waste treatment systems in refineries may be subjected to oil loadings sufficient to impair treatment efficiencies. Furthermore, deposits of oil scum create nuisances and increase operational problems.

Effects of various oil loadings on the performance of bench scale, activated sludge systems were investigated. The study considered oil loadings in the range of 13 to 625 mg/L in the systems. The oil and synthetic wastes were added daily to activated sludge units operating on a batch basis. Analyses included total organic carbon, volatile suspended solids, settleability, and pH.

The various oil loadings exhibited no drastic effects on TOC removal efficiency, pH, settleability, or volatile suspended solids. An increase in the color of the treated effluent at the three highest oil loadings was detected.

Hexane extractables were determined on the settled sludge, accumulated oil scum on the unit walls, and effluent. About 10 to 30 percent of the influent oil was recovered during these extractions. The balance appears to have been stripped or biologically degraded.

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# CHAPTER I

## INTRODUCTION

Oil in wastewaters under certain conditions can be detrimental to biological waste treatment systems since many bacteria cannot effectively decompose oil. However it has been shown that some bacteria obtained from wastewater will utilize oil as a substrate (17, 19, 20). Therefore conventional biological waste treatment processes function effectively only when the oil concentrations are not too great (12, 14).

The problem focuses not only on the crude oil refining and other petroleum-related industries which use biological waste treatment, but also on municipal facilities serving these and other industries. Gravity separation and flotation systems are widely used for oil recovery. Waste treatment facilities, however, are often subjected to oil concentrations sufficient to impair treatment efficiencies. The resulting effects are;

1. lower BOD removal efficiency (10),
2. floating oil-sludge scum in the effluent (5),
3. objectionable odors (5), and
4. maintenance problems such as deposit of this oil-sludge scum on facilities near the activated sludge units.

The laboratory investigation presented herein is concerned with effects of oil on biological waste treatment.

### Objectives

The primary purpose of this study was to determine specific effects of oil on the activated sludge process. The literature suggests that oil concentrations in excess of approximately one hundred milligrams per liter (mg/L) in wastewater are detrimental to treatment efficiencies (12, 14). It was desired to determine that concentration of oil in wastewater above which the

treatment efficiency is severely impaired. A second objective was to investigate the amenability of the oil to biological degradation.

Scope

A dual-phased laboratory investigation was preceded by a literature survey and followed by an evaluation of the collected experimental data.

Bench scale biological reactors were used in both phases to predict the effects of the oil at various concentrations on activated sludge. A control unit was subjected to wastewater without oil and comparisons were made using the following conventional waste treatment parameters;

1. total organic carbon(TOC) removal,
2. settleability,
3. effluent color,
4. volatile suspended solids concentration,
5. pH, and
6. hexane extractables in the effluent.

A light lubricating oil, similar to one which might find its way through the separation unit and into the waste treatment process of a crude oil refinery was used throughout the study.

Oil concentrations for the first experimental phase varied from about 13 to 100 mg/L (concentration after the wastewater was diluted in the mixed systems, "Mixed System Concentration") while that of the second stage varied from 63 to 625 mg/L. The second phase employed a more rigorous investigation of effluent oil concentration.

# CHAPTER II

## LITERATURE REVIEW

Most related literature published before 1950 deals with the effects of oily wastes on municipal waste treatment systems and procedures for determining oil and grease concentrations in wastewaters. Later, however, more research has been done by investigators studying the biodegradation of oil. Some of these reports were developed by industries.

### Early Investigations

Oil wastes have long been reported as being detrimental to effective biological wastewater treatment. In 1920, Kammann and Keim (1) wrote that oily wastewater from a refinery on the Ebe River near Hamburg, Germany was preventing proper biological treatment of sewage in septic tanks and sprinkling filters.

In the United States, urbanization and industrialization movements brought an increasing demand upon waste treatment facilities. With the increasing flows came an increase in oil and grease concentration. This oil and grease found its way to the treatment plants only to disrupt treatment efficiencies. The literature contains numerous investigations relating to analyses, effects, and treatment of such wastewaters (2, 3, 4).

Fales and Greeley (5) summarized the effects of these wastes on sewage treatment;

1. coating of particles of organic matter causing surface scum in settling tanks,
2. coating with a stable film surface what would otherwise be subject to microbial action,
3. clogging of trickling filters and trickling filter nozzels, and
4. offensive odors accompanying maintenance problems at the plants.

Most of the early work dealt with oil and grease jointly with the results being reported as "total grease" because of the convenient extraction procedures which did not differentiate the two. The usual definition of grease in sewage included "fats, waxes, free fatty acids, calcium and magnesium soaps, mineral oils, and non-fat materials" (5).

In 1941, Gehm and Trubnick (6) proposed a method for analysis of non-saponifiables for sewage investigation. Most data, however, continued to be reported as total grease. Several more recent articles, including work by Ullman et al. (7), present more accurate methods of hydrocarbon and fatty matter differentiation. The twelfth edition of Standard Methods for the Examination of Water and Wastewater (8), however, continues to suggest a method which reports both oil and grease together.

Accelerated industrial activities due to World War II accentuated the oil-grease waste problem. Brown (9) reported grease as the cause of an air consumption increase in activated sludge units and an interference with oxidation by trickling filters in Los Angeles. Wastes from defense industries in Lancaster, Pennsylvania resulted in similar findings. Bolenius (10) wrote that efficiencies of aeration were affected by primary effluents with as low as 60 mg/L grease. Other findings were;

1. a dissolved oxygen decrease within aeration tanks,
2. lower suspended solids,
3. higher total grease in the sludge,
4. oil being released slowly in the secondary effluent even when no oil was noticed in the primary effluent,
5. a longer time requirement for sludge drying, and
6. lower sludge digestion efficiencies.

## More Recent Investigations

More recent experimentation can be classified according to;

1. effects of the oil on the biological mass, i.e., effects on treatment

efficiency, and

2. the degradation of the oil by the biological mass.

Oily waste streams are of particular concern in petroleum refinery waste treatment practice. McKinney (11) states that process waters are free of separable oil. Oil may, however, originate from leaks, spills, tank draw-offs, and maintenance as well as repair activities from throughout a refinery (12). Gravity separators (API variety) are usually used to recover most of this oil. After passing through a separator where oil is skimmed off and recovered, the separator effluent contains about 40 mg/L of oil but may contain more than 100 mg/L when overloaded (11).

Coe (13) investigated the treatment of a refinery waste from thermal cracking, catalytic cracking and other petroleum processes. The average oil content of the waste after separation was found to be 25 mg/L. This concentration of dissolved oil was found to be non-detrimental to the treatment efficiency.

Weston (12) studied a typical refinery oil waste, and its effect on trickling filter removal efficiencies. He concluded that oil contents up to and including 100 mg/L will have no retarding effect on BOD removal. A significant part of the oil feed to the filter was not oxidized, however, and the sludge in the effluent settling tank contained oil equivalent to about thirty-one percent of the oil free solids content.

Austin et al. (14) reported similarly that BOD removal using a trickling filter was affected by high oil concentrations, but only at concentrations greater than 100 mg/L (with a loading of 28 Million Gallons Per Acre Per Day).

More recently, Hurwitz et al. (15) found that if oil was present even in "minute" concentration in a biological waste system it would coat the biological mass preventing contact with both the source of nitrogen (sewage) and the air required for the respiration process. Inhibition or complete failure of the process of sewage purification is reported as the result.

The amenability of oil to biochemical oxidation has been the subject

of several pertinent reports. In 1943, Duffet et al. (16) found that cutting oil samples contained large numbers of microorganisms usually of several species and genera. Fabian and Pivnick (17) grew bacteria in a variety of soluable oils, with soil, feces, river water, machine shop sweepings and pit sweepings as inocula. It was concluded that increasing the oil concentration of the emulsion decreases the mean generation time and increases the number of viable bacteria.

Using several varieties of oil and two genera of bacteria, Sabina and Pivnick (18), employing Warburg respiration techniques, reported that the different types of oils vary in their susceptibility to oxidation and that the bacteria vary in their capacity to oxidize a single soluable oil.

In 1945, Keefer (19) tested the amenability of oil and grease to biological oxidation. He noted ninety percent BOD removal for three grease concentrations (100,500 and 1000 mg/L) in 20 hours. The volume of settled sludge at the high concentration increased by fifty percent in ten hours. Keefer also investigated the treatability of cotton seed oil at various concentrations (BOD range, 104-570 mg/L) and reported ninety percent BOD removal in four hours at all concentrations.

Ludzack and Kinkead (20) performed experiments using medium grade commercial motor oil to determine the degree of bacterial oxidation under specific conditions. Mixed cultures for inoculation were collected from soils, refining cooling tower effluents, and freshly settled sewage.

Relating hydrocarbon reduction to carbon dioxide production, it was concluded that carbon dioxide was, in fact, the principle end product of oil in the aerobic oxidation system studied. Although many intermediate products in the biochemical oxidation of hydrocarbon are suggested as being possible, including peroxides, alcohols, diols, aldehydes, acids, ketones, ethers, and esters-- the most prominent were found to be organic acids and esters.

Using an initial oil concentration of approximately 100 mg/L, biological oxidation rates were determined at specific temperatures as shown in Table 1.

Table 1. BIOLOGICAL OXIDATION RATES AT SPECIFIC TEMPERATURES (20)

| temperature | oxidation of oil per week |
|---|---|
| 25°C | 50 to 80 % |
| 20°C | 30 to 50 % |
| 10°C | 20 to 30 % |
| 4°C | No apparent change |

Literature Evaluation

Pertinent conclusions made from research of the literature can be summarized as follows:

1. Oily waste streams can decrease the efficiency of biological waste treatment systems. Effects of oil and grease (usually reported inseparably) are observed to be;
   a. interference with microbial action by coating the floc or clogging trickling filters,
   b. offensive odors,
   c. buildup of grease in the sludge,
   d. dissolved oxygen decrease in aeration tanks,
   e. floating oil-sludge scum in the effluent, and
   f. maintenance problems.
2. It appears that oil concentrations of less that 100 mg/L have little noticeable effect on treatment except for oil buildup in the sludge.
3. Bacteria found in wastewater will utilize oil as a substrate. The oxidation rate is dependent upon temperature (Table 1), degree of acclimation, and type of oil.

## CHAPTER III

## EXPERIMENTAL PROCEDURES

A dual-phased experimental program was employed with the primary difference in phases being the range of oil concentration in the wastewater. The range of oil in the wastewater of the first phase was 13 to 100 mg/L (mixed system concentration) while that of the second phase was 63 to 625 mg/L. The first phase gave an opportunity to determine the most practical analytical procedures to be used in measuring the parameters of interest. Furthermore, the results of the first phase stimulated interest as to the fate of the oil, i.e., what percent of influent oil was oxidized, what percent was discharged with the effluent, and what percent adhered to the biological floc either in the mixed liquor or in the oil-sludge scum which adhered to the walls. A more rigorous attempt was made in the second phase to determine a material balance of the oil.

### Waste Characterization

A synthetic waste was used for acclimation and throughout this experimentation. In addition to dextrose, the carbon source, compounds were added to contribute nitrogen and phosphorus and also serve to buffer the system. The waste was prepared weekly and stored at 4°C to prevent biodegradation.

Eckenfelder and Cardenas (22) recommend a minimum concentration of nitrogen and phosphorus to give a BOD to-nitrogen to-phosphorus ratio (BOD:N:P) of 60:3:1 for wastewater that is to be treated biologically. Much higher relative concentrations with a ratio of 100:50:10 were required to produce satisfactory settling when using this dextrose waste.

Ford and Eckenfelder (21) recommend a food to microorganism ratio (F:M) of 0.1 to 0.8 (lb BOD/day/lb MLSS) for activated sludge treatment of

domestic sewage. Because of the nature of dextrose when used as a synthetic sewage carbon source, it was necessary to use a low value (0.33) in this range to prevent the predominance of filimentous growth and thus insure desirable settling characteristics.

The same F:M and BOD:N:P were used for each experimental phase. The dextrose concentration (and thus the N and P concentrations) of the waste, therefore, was adjusted for the desired volatile solids range.

Tables 2 and 3 describe the respective wastes of the two phases of experimentation. Waste characteristics as reported are based upon the concentration of the waste added, and not on the total volume of the unit. To obtain the diluted concentration, these values must be divided by 1.6 (the volume of each unit). This diluted concentration is referred to as "mixed system concentration" throughout this report. For example, oil concentrations in wastewater in the first phase for units 1, 2, 3, 4 and 5 were 0, 20, 40, 80, and 160 mg/L respectively. Mixed system concentrations, however, were 0, 13, 25, 50, and 100 mg/L respectively. For the second phase, wastewater oil concentrations for units 1, 2, 3, 4, and 5 were 0, 100, 200, 500, and 1000 while mixed system concentrations were 0, 63, 125, 313, and 625 mg/L.

Desired quantities of oil were added daily to each unit containing the synthetic wastes. A syringe (5 cc volume, B-D Yale Model - a product of Becton Dickinson and Co., with a No. 25 needle) was used to add small drops of oil. Initially, the weight of each drop was found to be $4.84 \pm 0.05$ milligrams and analysis after experimentation found it to be $5.03 \pm 0.08$ milligrams. Each drop was assumed to weigh 5.00 milligrams.

The light lubricating oil used might have resulted from spills, leaks, or blowdown within a refinery. Table 4 is a summary of the analyses of a sample of the oil used.

Table 2. WASTE CHARACTERISTICS

FIRST PHASE

| Components of the Synthetic Wastewater | Concentration (mg/L) |
|---|---|
| Dextrose | 400 |
| Sodium Bicarbonate | 200 |
| Ammonium Chloride | 600 |
| Sodium Phosphate | |
| Monobasic | 200 |
| Dibasic | 200 |
| Nitrogen | 156 |
| Phosphorous | 31 |

| Analysis | Unit No. | | | | |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 |
| Measured TOC (mg/L) | 159 | 149 | 155 | 154 | 168 |
| Theoretical TOC (mg/L) | --- | 163 | 167 | 173 | 188 |
| Measured BOD (mg/L) | 240 | 248 | 240 | 270 | 216 |
| Theoretical BOD (mg/L) | --- | 244 | 248 | 256 | 272 |
| Oil Added | | | | | |
| Wastewater Conc. (mg/L) | 0 | 20 | 40 | 80 | 160 |
| Mixed System Conc. (mg/L) | 0 | 13 | 25 | 50 | 100 |
| Syringe drops | 0 | 4 | 8 | 16 | 36 |

Table 3. WASTE CHARACTERISTICS

SECOND PHASE

| Components of the Synthetic Wastewater | Concentration (mg/L) |
|---|---|
| Dextrose | 800 |
| Sodium Bicarbonate | 400 |
| Ammonium Chloride | 1200 |
| Sodium Phosphate | |
| Monobasic | 400 |
| Dibasic | 400 |
| Nitrogen | 312 |
| Phosphorous | 62 |

| Analysis | Unit No. | | | | |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 |
| Measured TOC (mg/L) | 336 | 336 | 348 | 432 | 564 |
| Theoretical TOC (mg/L) | --- | 354 | 372 | 426 | 516 |
| Measured BOD (mg/L) | 705 | 750 | 833 | 855 | 925 |
| Theoretical BOD (mg/L) | --- | 725 | 744 | 803 | 900 |
| Oil Added | | | | | |
| Wastewater Conc. (mg/L) | 0 | 100 | 200 | 500 | 1000 |
| Mixed System Conc. (mg/L) | 0 | 63 | 125 | 313 | 625 |
| Syringe Drops | 0 | 20 | 40 | 100 | 200 |

Table 4. OIL CHARACTERISTICS

| analysis | concentration (mg/L) |
|---|---|
| BOD (5 day) | 195,000 |
| TOC | 180,000 |
| COD | 852,000 |

The United States Bureau of Standards states that lubricating oils contain from 18 to 26 percent straight and branched chained paraffins, 43 to 51 percent alkylated napthenes (1, 2, 3 rings), and 8 percent asphaltic substances (largely aromatic) (23). No analysis other than that reported in Table 4 was conducted to classify the oil used in this experimentation.

Two values for both BOD and TOC are reported in Tables 2 and 3 for each waste. Difficulty was experienced in thoroughly dispersing the oil. Therefore, truly representive samples could not be analyzed, and consequently it was decided to report a corresponding "theoretical" TOC and BOD with each "measured" value. The "theoretical" values are based upon that determined TOC or BOD of the waste for the control unit (containing no oil) plus that expected contribution from the diluted oil. A representative BOD of the oil is estimated to 195,000 mg/L and a representative TOC is estimated to be 180,000 mg/L (Table 4). The BOD was determined using seed which had been acclimated to the oil as a feed and a blender was used to homogenize diluted TOC samples. The BOD of the synthetic waste for the control unit of the first phase was determined to be 240 mg/L. That expected BOD of the waste for unit 5 of the first phase due to the diluted oil is:

$$\frac{0.160 \text{ (gm oil)}}{1000 \text{ (gm water)}} \times 195{,}000 \text{ (BOD of oil)} \simeq 32 \text{ mg/L}$$

The "theoretical" BOD for unit 5 of the first phase, therefore, was 240 + 32 = 272 mg/L. This value is compared to the "measured" value of 216 mg/L. For the first phase, the "theoretical" values were usually greater than the "measured' values.

In an effort to obtain a more representative sample for BOD and TOC analyses for the second phase, a Waring blender was used to homogenize the sample and disperse the oil. For unit 5, second phase, the theoretical TOC was 336 (measured TOC of the control waste) + 180 ( $\frac{1.000}{1000}$ X 180,000) = 516 mg/L as compared to a "measured" value of 564 mg/L. Figure 1 shows the BOD - TOC relationships resulting from biodegradation of the wastes for both experimental phases. Data points for wastes with the lower oil concentrations do not correlate properly and are indicative of the experimental error due to difficulty in obtaining representative samples. Points for raw waste with higher oil concentrations compare more favorably.

Apparatus and Methodology

Bench scale activated sludge units were used as biological reactors. Sludge from an Austin sewage treatment plant was acclimated according to a method suggested by Eckenfelder and Cardenas (22), but modified to a semi-continuous system. The sludge (1.6 liters) was introduced into each of 5 plexiglass units (Figure 2). One liter of synthetic waste was introduced to each unit on a semi-continuous schedule (daily) after the mixed liquor had been allowed to settle for one hour and one liter of supernatant had been withdrawn. No oil was added with the synthetic waste during acclimation.

The air supply was from a wall outlet (14 psi) and was filtered through glass wool prior to being channelled to the individual diffusers at 0.1 cfm.. The operating temperature was maintained at 18°C.

After ten days, the activated sludge system was assumed to be acclimated. The volatile solids concentration was approximately 1000 mg/L for

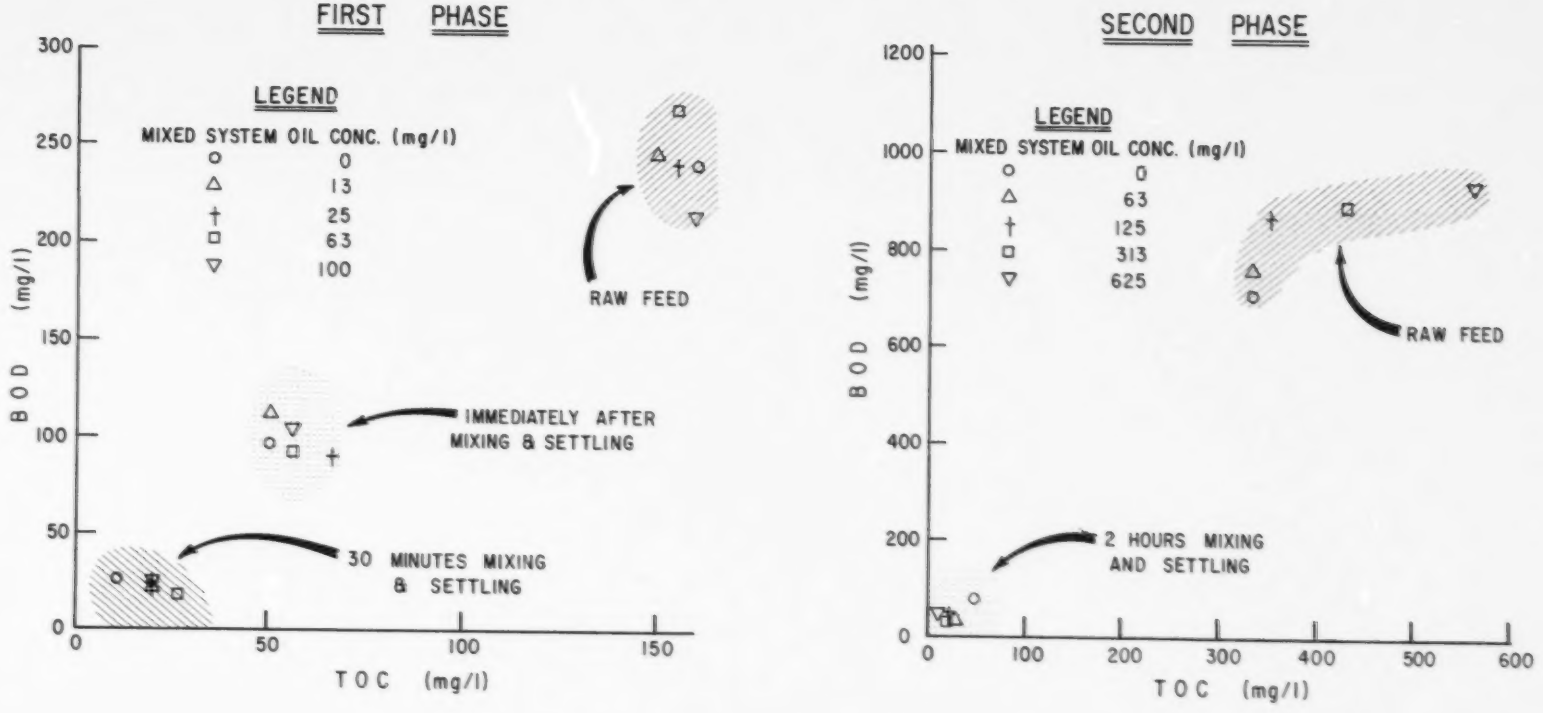



FIG. 1. BOD-TOC RELATIONSHIPS

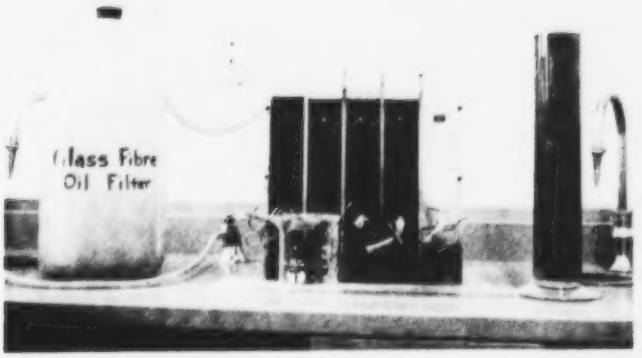



Figure 2. BENCH SCALE ACTIVATED SLUDGE UNITS

each unit of the first phase and 2000 mg/L for the second phase. TOC removal efficiency exceeded 90 percent for each unit (both filtered and unfiltered samples) and pH measurements were well within that range (6-8) recommended by Eckenfelder and Cardenas (22).

Feeding procedures were the same after acclimation except that oil was added to units 2, 3, 4, and 5. Unit 1 was used as a control in order to make justifiable comparisons. Synthetic sewage was fed daily with no oil added.

TOC, settleability, total and volatile solids, and pH analyses were performed on the mixed liquor prior to feeding and after 24 hours of aeration. Data was collected daily for the first 10 days, weekly for the next 30 days, and finally, after 90 days during the first phase when extractions were performed. Analyses were performed daily for 15 days in the second phase.

After 90 days' observation of the units of the first phase it was desired to investigate the fate of the oil which had been added to each unit. Extraction procedures were applied to the effluent, mixed liquor, and oily scum in an effort to obtain a mass balance. Similar procedures were applied in the second phase except that hexane extraction was determined daily on settled effluent samples.

## Analytical Methods

Analyses were in accordance with the procedures outlined in Standard Methods (8) with modifications as noted.

1. Solids Determination. Glass fiber filters (a product of Reeve Angel) and gooch crucibles were employed. Analysis was duplicated for each sample.
   a. Total Suspended Solids. The samples were heated to 103°C overnight to insure dryness.
   b. Volatile Suspended Solids. The samples were ignited to 600°C

for 20 minutes. The percent weight loss of the filters was determined to be $1.32 \pm 0.51$ which was considered insignificant.

2. pH. The hydrogen ion concentration of the feed and the mixed liquors was measured using a Beckman "Model H" pH meter equipped with a glass electrode. A calomel electrode was used as the reference. The pH meter was standardized against a buffer solution with a pH approaching that of the sample and the linearity of the electrode response was checked with one additional buffer of a different pH.

3. Settleability. The one liter of sludge required for the standard settleability test constituted the majority of each unit's volume. After the sludge had settled for an hour in a 1000 milliliter graduated cyclinder, the supernatant was withdrawn by siphoning. The sludge left in the unit was also allowed to settle. A volume of its supernatant equal to that of the settled sludge in the graduated cyclinder was drained from each unit. The settled sludge was poured back into the unit before feeding. This procedure limited quiescent time to 1 hour and assured drainage of one liter per day while a minimum of solids was wasted in the supernatant. Approximately 50 milliliters of mixed liquor was required for solids and pH analysis and thus wasted daily.

4. Biochemical Oxygen Demand (BOD). The 5-day BOD of the feed was determined using the Modified Azide Method for estimating dissolved oxygen as suggested in Standard Methods (8).

5. Total Organic Carbon (TOC). A Beckman Carbonaceous Analyzer (Appendix A) was utilized. Samples were often stored overnight at $4^{\circ}$ C after the addition of concentrated HCl to prevent further biological degradation. It was decided to examine both settled (supernatant) and filtered samples for TOC. Ten milliliters of supernatant were withdrawn for each unit after one hour of

settling. The filtered samples were simply the filtrate from the solids tests. Duplicates were analyzed for both filtered and settled supernatant.

6. Extractions. N-hexane was used as the solvent in lieu of petroleum ether and evaporation by air stream was substituted for the distillation techniques of Standard Methods (8).

7. Color. Color was determined using a Hellige comparator.

## CHAPTER IV

## RESULTS AND DISCUSSION

A dual experimental program was undertaken to evaluate effects of oil on an activated sludge treatment unit. The range of oil concentrations in the first phase was 13 to 100 mg/L while that of the second phase was 63 to 625 mg/L. Results were analyzed for each program or phase. A summary of the daily analyses, namely volatile suspended solids, TOC removal efficiency, settleability, and pH are included in Appendix B.

### Total Organic Carbon Removal

Total organic carbon removal was used to evaluate treatment efficiencies. The effluent was analyzed after 24 hours of aeration. Two types of samples were analyzed: "Filtered"(filtrate from suspended solids analyses), and "Settled"(supernatant after one hour of quiescent settling of the mixed liquor). TOC removal efficiencies were computed as follows:

$$\text{TOC efficiency (\%)} = \frac{TOC_o - TOC_e}{TOC_o} \times 100$$

where: $TOC_o$ = TOC of influent waste (mg/L)

$TOC_e$ = TOC of effluent waste (mg/L)

Figures 3 and 4 show TOC removal efficiency values for each of the oil loadings and the controls. The first phase (Figure 3) data are presented from the fifth through the forty-first days. The first five days were used for additional acclimation. For the second phase, the sludge was well acclimated to the synthetic waste before oil addition, and data are presented for the fifteen days of testing. The following is an evaluation of these data.

Based on the results of the first phase of study, the lower oil loadings had no apparent deleterious effect on treatment efficiency. TOC of the settled effluent samples was higher than that of the filtered samples, even for the control. The biological floc particles which remained in suspension

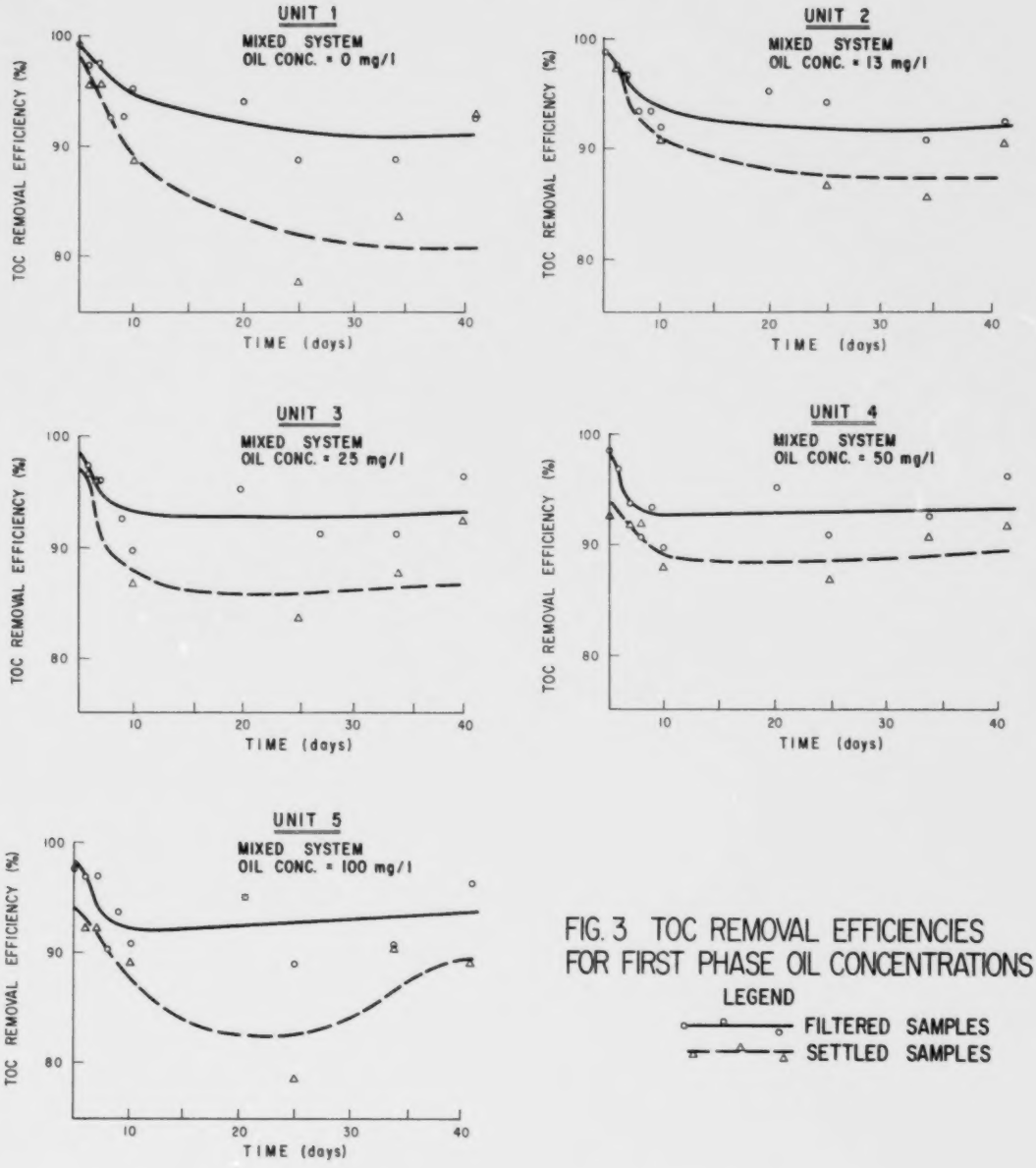
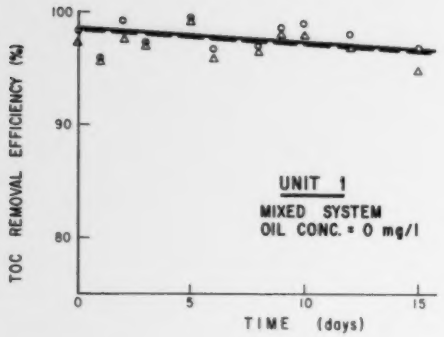


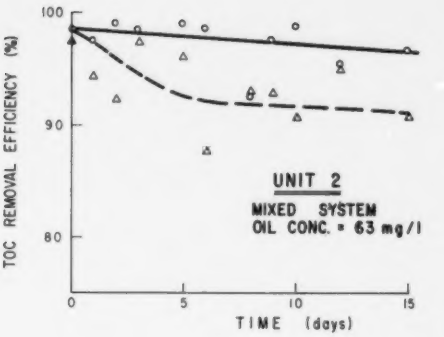

FIG. 3 TOC REMOVAL EFFICIENCIES FOR FIRST PHASE OIL CONCENTRATIONS

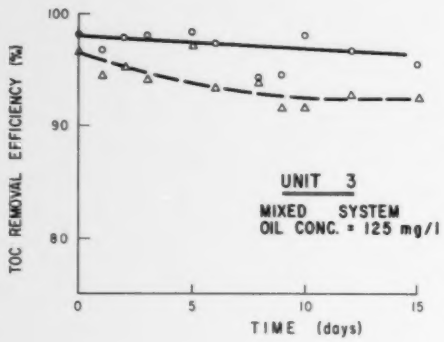
LEGEND

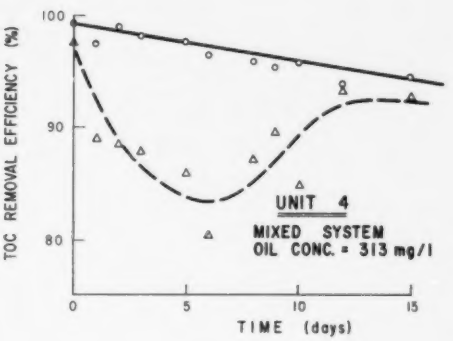
FILTERED SAMPLES

SETTLED SAMPLES



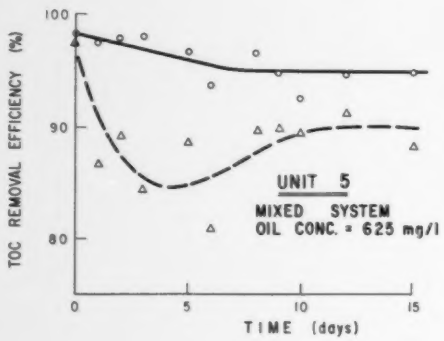




FIG. 4 TOC REMOVAL EFFICIENCIES FOR SECOND PHASE OIL CONCENTRATIONS

LEGEND

FILTERED SAMPLES

SETTLED SAMPLES

after one hour of settling accounted for the increased TOC. Reproducibility of TOC data was more difficult to obtain for the settled samples because of the presence of floc. Generally, efficiencies were not lower at any oil concentration than for the control.

Although a difference in TOC had been noticed between settled and filtered effluent samples of the control of the first phase, this was not true of the control unit in the second phase. A possible explanation is that the higher suspended solids concentration in the control unit of the second phase helped to attain more complete clarification. More total organic carbon was found in the effluent samples at the higher oil loadings of the second phase. From Figure 4, a decrease in TOC removal efficiency is noted for the first ten days. Higher efficiencies after ten days indicate that the biomass had become acclimated to the oil.

At the oil loading of 313 mg/L, efficiencies were considerably smaller than at any of the lower oil loadings. Efficiencies were also considerably smaller at 625 mg/L, but no smaller than those at 313 mg/L oil. Even the lowest efficiency values at the highest oil loadings, however, were greater than 78 percent.

Color

Settled effluent from unit 5, second phase (625 mg/L mixed system oil concentration), seemed to be more turbid than any of the other units. On the fifth day of analysis, a distinct yellow color was noticed in the settled effluent from unit 5 with lighter shades in units 3 and 4. Examination using a Hellige Comparator gave the values presented in Table 5.

Table 5. COLOR COMPARISONS

| Unit No. | Mixed System Oil Conc. (mg/L) | Color Units | |
|---|---|---|---|
| | | Filtered | Settled |
| 1 | 0 | 0 | 0 |
| 2 | 63 | 0 | 5 |
| 3 | 125 | 5 | 5 |
| 4 | 313 | 5 | 10 |
| 5 | 625 | 15 | 15 |

The color appeared in effluents for the remainder of the analysis period. Although, no higher TOC values were indicated in the effluent of unit 5, color was considerably greater for unit 5 than for unit 4.

Settleability

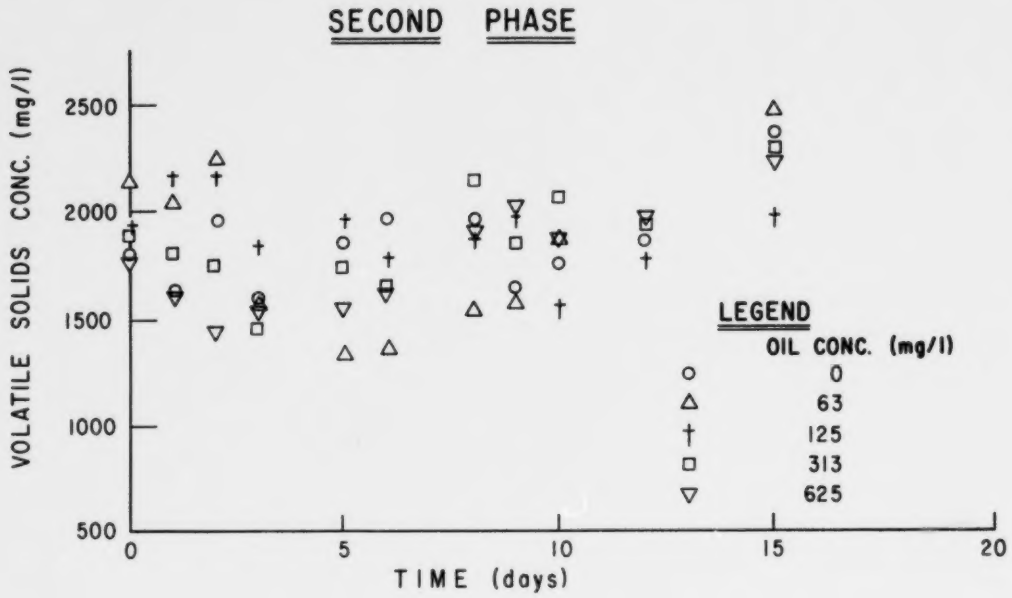
Sludge Volume Index (SVI) as recommended by Standard Methods (8) was used to evaluate the effects of oil on sludge settleability. SVI is defined as follows:

$$SVI = \frac{\text{ml settled sludge (after 30 min.)}}{\text{grams suspended matter / Liter}}$$

A general decline in SVI was noted with time for each oil concentration, Figure 6. Volatile solids concentration remained relatively constant in each case, although the sludge seemed to compact a little more each day. The higher oil concentrations of the second phase seemed to have little effect on settleability.

Suspended Solids

From the results of this study, no increase or decrease in volatile suspended solids can be related to oil loading. Volatile solids remained relatively constant for each unit of each phase, Figure 5. A slight increase of volatile solids was noticed after approximately twenty days of operation during the first phase and five days during the second phase. No sludge was wasted, excepting the 50 milliliters which was used on days of testing.



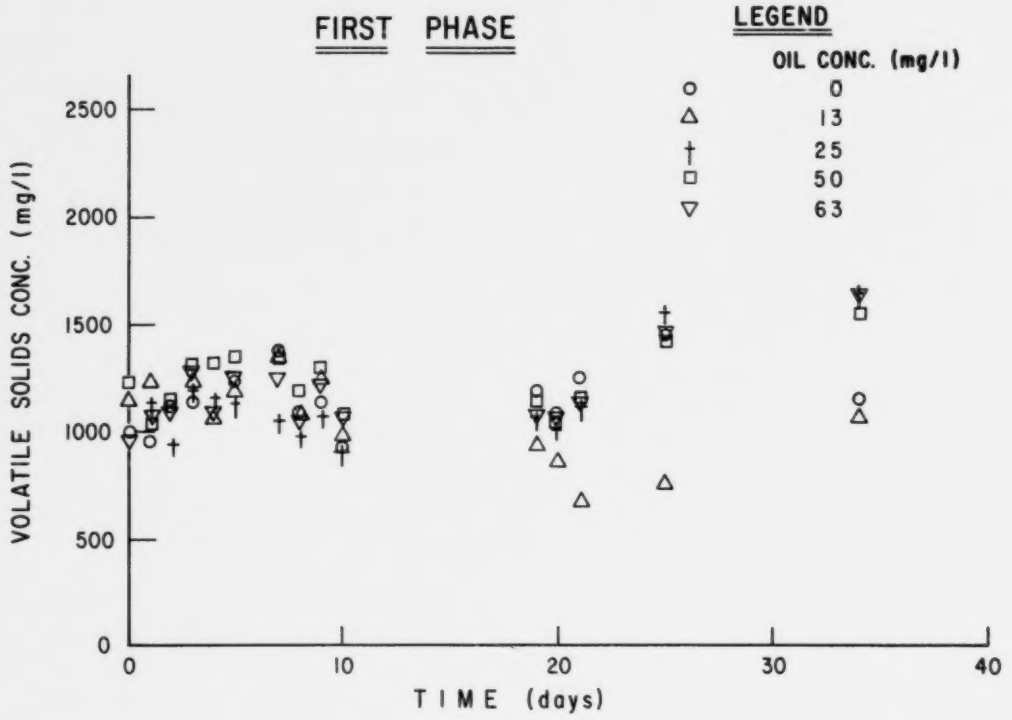




FIG. 5. VOLATILE SUSPENDED SOLIDS

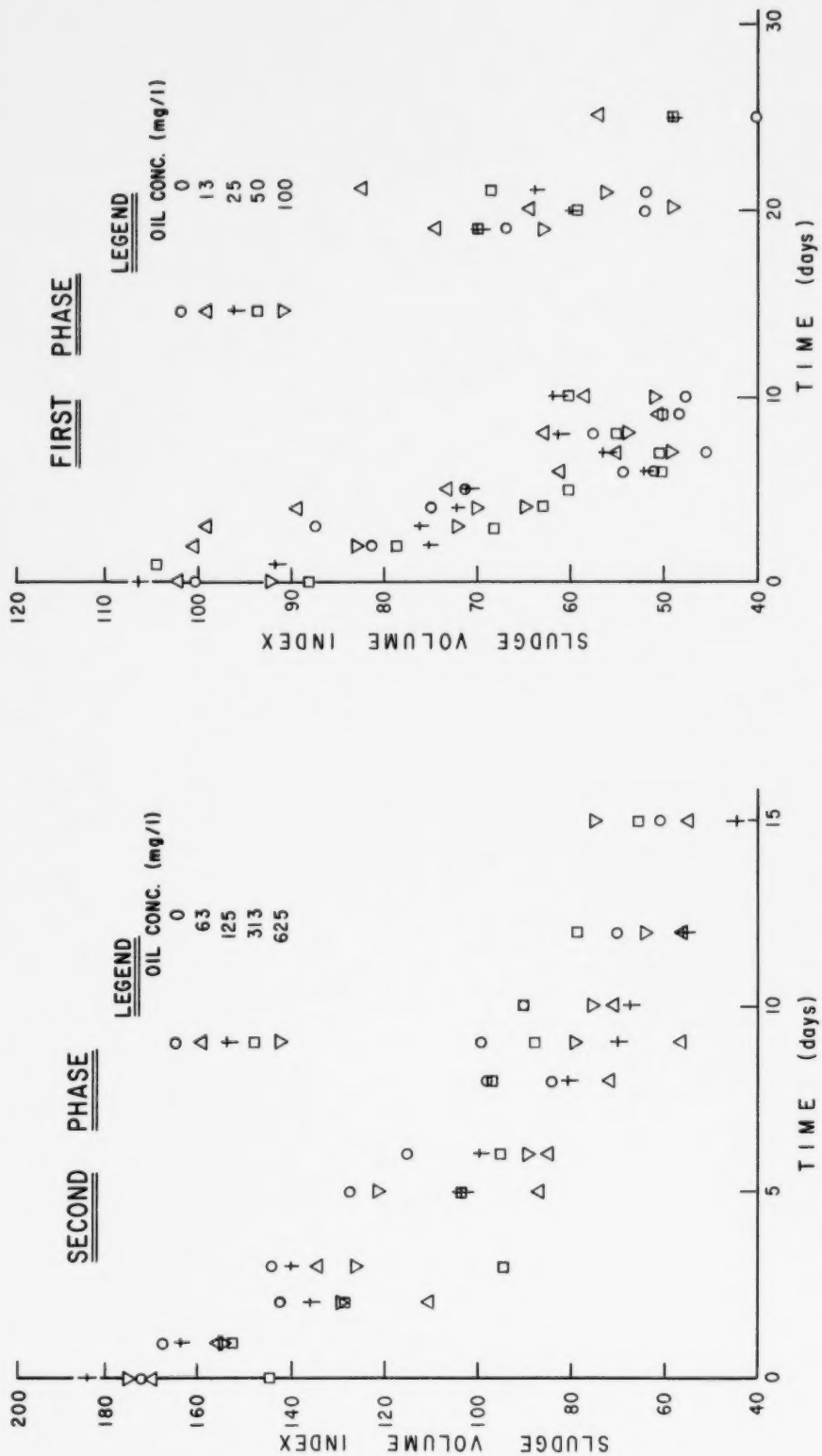



FIG. 6. SLUDGE VOLUME INDICES

The organic strength of the waste for the second phase was increased over that of the first phase in an effort to maintain approximately 2000 mg/L mixed liquor volatile suspended solids concentration. This more closely simulated field conditions.

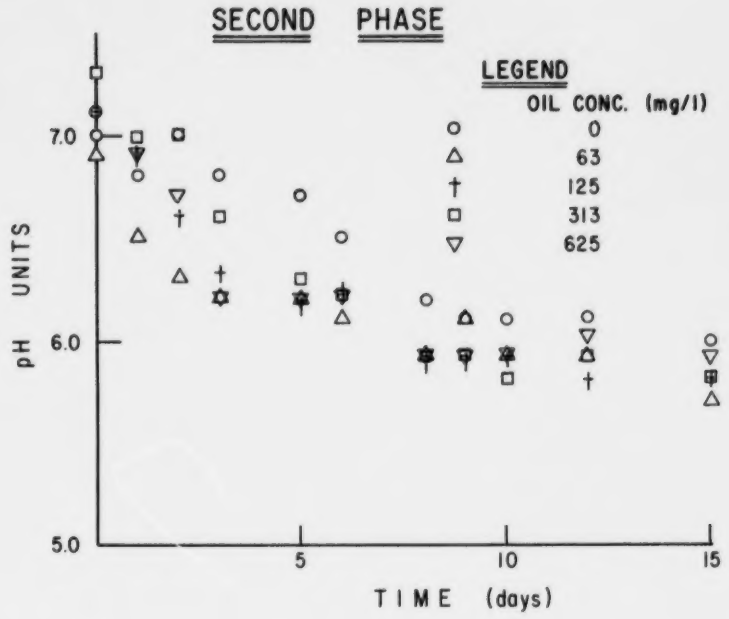
Hydrogen Ion Concentration

No relationship seemed to exist between pH in the aeration unit and various oil loadings, Figure 7. The initial pH of the synthetic waste was 7.1 and that of the oil, 6.7. A decrease in pH with time occurred in both the control unit and the units receiving oil. In both phases, however, the pH of the control (although decreasing) maintained a slightly greater pH than the units being subjected to the oil.

Oil Extractions

Oil loadings resulted in an accumulation of oil scum over the liquid and on the walls of the activated sludge units. Similarly, a small accumulation of biological scum was noticed on both control units, but no oil was apparent. As oil was added each day to certain units a scum formed on the liquid surface and persisted for approximately two hours. A spray of this relatively lightweight material was deposited to a height of approximately six inches above the water surface. More oil and scum were noticed when the oil concentrations were higher. Each day most of the scum was rinsed back into the mixed system with influent wastewater. Within two hours, however, deposited scum was again apparent on the walls.

No daily effort was made during the first phase to determine hexane extractables in the effluent. Before discarding the sludge from the first experiment, analyses were conducted in an effort to determine that amount of oil which had been retained in the units. Oil was extracted from 100 ml samples of mixed sludge from each unit, and the scum from the walls of



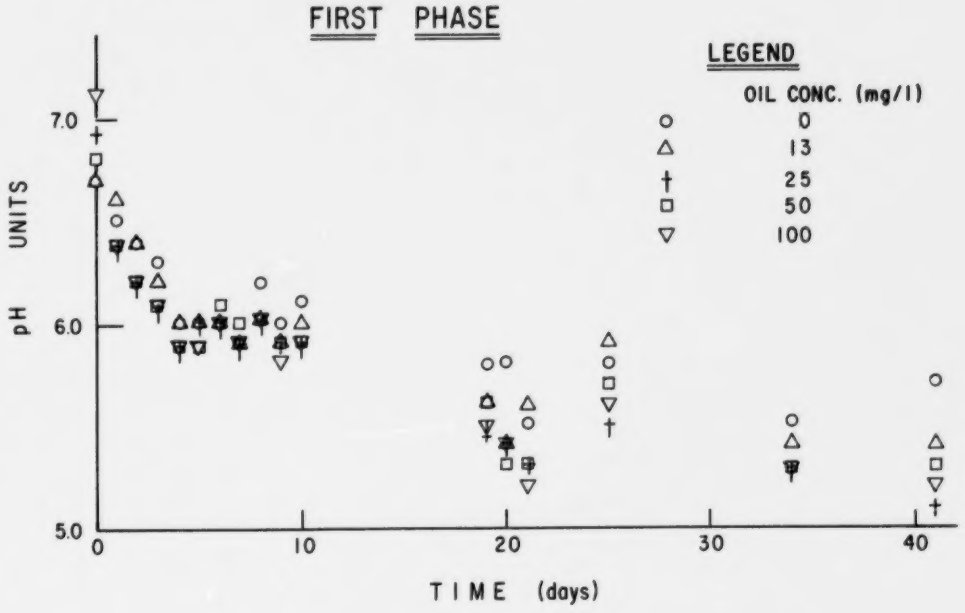




FIG. 7. pH OF MIXED SYSTEMS

each unit. Difficulty was experienced in recovering the oil, but the data presented in Table 6 are believed to be representative.

Approximately 12 to 20 percent of the oil was recovered for each loading of the first phase and the balance is believed to have been:

1. wasted with the effluent,
2. "stripped out" to the atmosphere as volatile hydrocarbons, or
3. converted to an end or intermediate biological product by the bacteria in the mixed system.

More scum was noticed on the walls of the units with higher oil loadings of the second experimental phase. As in the first phase, a surface scum formed upon waste addition but persisted longer (about four hours). After eight days, the scum on the liquid water surface of unit 5 (one gram of oil added each day) persisted on the surface after 24 hours aeration. This scum was not removed with each day's effluent because as the effluent was drained, the oil scum adhered to the unit walls, only to be resuspended as the new raw waste was added. The amount of this oil scum increased daily, and oil recovery analyses were performed on the fifteenth day.

A more rigorous attempt was made to determine the fate of the oil in the second phase of experimentation. Analysis for hexane extractables was performed daily in an effort to detect a significant oil loss in the effluent. When compared to the control unit, only unit 5 provided consistantly higher losses. An average of about 2.4mg of oil loss per 100 ml effluent was recovered in unit 5 by extractions. This indicates a loss of approximately 24 mg per day from unit 5 or 2.4 percent which is indicated in Table 6.

Settled sludge from one liter of mixed activated sludge was analyzed for oil before it was discarded. A significant amount was found only in the settled sludge from unit 5 (1000 mg/L oil added daily). About 581.3 mg of the total oil added was found to be associated with the settled sludge of

Table 6. SUMMARY OF OIL RECOVERY DATA

| | OIL ADDED (gm) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | First Phase Unit No. | | | | | Second Phase Unit No. | | | | |
| | 1 | 2 | 3 | 4 | 5 | 1 | 2 | 3 | 4 | 5 |
| per day | 0 | 0.020 | 0.040 | 0.080 | 0.160 | 0 | 0.100 | 0.200 | 0.500 | 1.000 |
| total | 0 | 1.800 | 3.600 | 7.200 | 14.400 | 0 | 1.500 | 3.000 | 7.500 | 15.000 |

| | OIL RECOVERED (gm) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | First Phase Unit No. | | | | | Second Phase Unit No. | | | | |
| | 1 | 2 | 3 | 4 | 5 | 1 | 2 | 3 | 4 | 5 |
| from sludge | 0.094 | 0.146 | 0.026 | 0.196 | 0.164 | 0.008 | 0.007 | 0.006 | 0.012 | 0.582 |
| from walls | ----- | 0.171 | 0.401 | 1.233 | 1.593 | 0.010 | 0.256 | 0.654 | 2.320 | 3.152 |
| total recovered | 0.094 | 0.317 | 0.427 | 1.429 | 1.757 | 0.018 | 0.263 | 0.660 | 2.332 | 3.734 |
| percent recovered | ----- | 17.60 | 11.85 | 19.85 | 12.20 | ----- | 17.52 | 22.00 | 31.10 | 24.90* |

* Includes that approximately 2.4% estimated loss in effluent

unit 5. A much smaller amount was found for the other four units. It is interesting to note that this 0.581 gm of oil assoicated with the unit 5 sludge had no noticeable effect on settleability (Figure 7) during the fifteen days of observation.

As in the first phase, scum was carefully recovered from the plexiglass units and extracted for oil. Generally, a higher percent of wastewater influent oil was recovered for each unit than for the lower oil loadings of the first phase. Results of oil recovery for the second phase are presented in Table 6.

No attempt was made to recover any fraction of oil which might have been "stripped out" as volatile hydrocarbons. The percent oil recovery increased with oil loading in the second phase, the exception being unit 5 (1.0 gm oil added daily). Possibly more stripping occurred in unit 5.

## CHAPTER V

## CONCLUSIONS

1. Total organic carbon removal from wastewaters containing oil, using semi-continuous, bench scale activated sludge units, was not drastically affected by various oil loadings. Efficiencies for oil concentrations of 13, 25, 50, 63, 100 and 125 mg/L oil in the systems differed only slightly from the control containing no oil. At the two highest oil loadings, (313 and 625 mg/L oil), the efficiencies were lower as compared to the control but even in these cases the removal efficiencies were greater than 80 percent.
2. The oil did not completely mix with the system, but accumulated on the walls of the treatment units above the liquid surface. Some oil was also found to be associated with the settled sludge while hexane extractables in the effluents were determined to be significant only at the highest oil loading (625 mg/L oil). Recovered oil varied between 10 and 30 percent of the total oil applied during the experimental period. Generally a greater percent of the applied oil was recovered from those units subjected to the higher oil loadings. The remainder was stripped or degraded biologically.
3. Increased turbidity and color were noticed in the effluents from the systems containing 125, 313, and 625 mg/L oil. The corresponding color analysis indicated 5, 10, and 15 color units for the respective effluents.
4. Settleability, volatile suspended solids concentration, and pH seemed to be independent of oil loading for the systems studied.

# APPENDIX A

## Appendix A

## BECKMAN CARBONACEOUS ANALYZER (24)

The Beckman Carbonaceous Analyzer is operated on the principal that organic material will oxidize in the presence of pure oxygen gas resulting in the production of a given amount of carbon dioxide.

A very small amount of sample is introduced to the combustion tube of the instrument by a hypodermic syringe. The combustion tube which contains an asbestos packing coated with a cobalt oxide catalyst is heated to approximately 950°C. Any organic material in the sample is completely oxidized to carbon dioxide by the constant stream of pure oxygen flowing through the combustion tube.

The carbon dioxide is transported by the oxygen through an infrared analyzer. The signal from the infrared analyzer indicates the quantity of carbon dioxide (e.g., carbon content of the sample) present in the oxygen stream (24). The instrument is calibrated by carbon dioxide-free acetic acid standards.

To facilitate measuring only the organic carbon, the dissolved carbon dioxide, bicarbonated, and carbonated that may be present are driven off by acidifying the sample to a level below pH 1.5 and purging it with nitrogen gas. When volatile organics are present, another procedure has to be followed to distinguish organic carbon from carbonates and carbon dioxide (24).

# APPENDIX B

Table B-1. SUMMARY OF DATA FOR UNIT 1, FIRST PHASE

Oil Concentration (mixed system) = 0 mg/L

| Day | TOC Removal Efficiency (%) Filtered | Settled | Sludge Volume Index | Suspended Solids (mg/L) Total | Volatile | pH |
|---|---|---|---|---|---|---|
| 0 | 94.4 | 85.6 | 100.5 | 1093 | 1000 | 6.7 |
| 1 | 93.8 | 81.2 | 130.0 | 990 | 970 | 6.5 |
| 2 | 92.5 | 86.2 | 81.3 | 1417 | 1116 | 6.4 |
| 3 | 92.0 | 91.2 | 87.1 | 1273 | 1147 | 6.3 |
| 4 | 96.3 | 92.6 | 74.6 | 1340 | 1040 | 6.0 |
| 5 | 99.2 | ---- | 71.5 | 1400 | 1230 | 6.0 |
| 6 | 97.5 | 95.4 | 54.2 | 1290 | ---- | 6.0 |
| 7 | 97.7 | 95.4 | 45.6 | 1537 | 1380 | 5.9 |
| 8 | 92.6 | ---- | 57.5 | 1217 | 1063 | 6.2 |
| 9 | 92.6 | ---- | 48.5 | 1235 | 1133 | 6.0 |
| 10 | 95.1 | 88.7 | 47.9 | 1042 | 912 | 6.1 |
| 19 | ---- | ---- | 65.0 | 1230 | 1190 | 5.8 |
| 20 | 94.3 | ---- | 52.5 | 1238 | 1093 | 5.8 |
| 21 | ---- | ---- | 52.4 | 1240 | 1133 | 5.5 |
| 25 | 88.6 | 77.4 | 39.1 | 1535 | 1450 | 5.8 |
| 34 | 88.6 | 83.7 | 32.4 | 1390 | 1155 | 5.5 |
| 41 | 92.5 | 92.4 | ---- | ---- | ---- | 5.7 |

Table B-2. SUMMARY OF DATA FOR UNIT 2, FIRST PHASE

Oil Concentration (mixed system) = 13 mg/L

| Day | TOC Removal Efficiency (%) Filtered | Settled | Sludge Volume Index | Suspended Solids (mg/L) Total | Volatile | pH |
|---|---|---|---|---|---|---|
| 0 | 94.0 | 83.2 | 102.2 | 1270 | 1147 | 6.7 |
| 1 | 93.2 | 79.8 | 119.0 | 1220 | 1203 | 6.6 |
| 2 | 91.9 | 84.5 | 100.1 | 1400 | 1083 | 6.4 |
| 3 | 95.9 | 89.3 | 99.0 | 1357 | 1213 | 6.2 |
| 4 | 95.9 | 91.9 | 89.2 | 1290 | 1033 | 6.0 |
| 5 | 98.7 | ---- | 73.1 | 1437 | 1190 | 6.0 |
| 6 | 97.3 | 97.3 | 60.4 | 1223 | ---- | 6.0 |
| 7 | 96.4 | 96.4 | 54.7 | 1503 | 1350 | 5.9 |
| 8 | 93.2 | ---- | 62.7 | 1277 | 1082 | 6.0 |
| 9 | 93.2 | ---- | 51.0 | 1370 | 1213 | 5.9 |
| 10 | 91.9 | 90.6 | 57.7 | 1127 | 990 | 6.0 |
| 19 | ---- | ---- | 74.2 | 945 | 930 | 5.6 |
| 20 | 95.9 | ---- | 63.7 | 943 | 848 | 5.4 |
| 21 | ---- | ---- | 82.3 | 730 | 680 | 5.6 |
| 25 | 94.0 | 86.5 | 56.8 | 792 | 758 | 5.9 |
| 34 | 90.6 | 85.8 | 46.0 | 1301 | 1078 | 5.4 |
| 41 | 92.6 | 90.6 | ---- | ---- | | 5.4 |

Table B-3. SUMMARY OF DATA FOR UNIT 3, FIRST PHASE

Oil Concentration (mixed system) = 25 mg/L

| Day | TOC Removal Efficiency (%) Filtered | Settled | Sludge Volume Index | Suspended Solids (mg/L) Total | Volatile | pH |
|---|---|---|---|---|---|---|
| 0 | 94.0 | 85.3 | 106.0 | 707 | 623 | 6.8 |
| 1 | 93.6 | 85.3 | 91.4 | 1203 | 1123 | 6.4 |
| 2 | 93.0 | 89.0 | 75.0 | 1263 | 963 | 6.2 |
| 3 | 96.0 | 91.5 | 76.0 | 1477 | 1187 | 6.1 |
| 4 | 96.0 | 92.4 | 71.8 | 1393 | 1120 | 5.9 |
| 5 | 98.8 | ---- | 70.4 | 1277 | 1140 | 5.9 |
| 6 | 97.2 | 96.6 | 52.1 | 1317 | ---- | 6.1 |
| 7 | 96.0 | 96.0 | 55.5 | 1170 | 1047 | 6.0 |
| 8 | 93.7 | ---- | 61.0 | 1148 | 983 | 6.0 |
| 9 | 92.3 | ---- | 50.0 | 1198 | 1050 | 5.9 |
| 10 | 89.6 | 86.5 | 62.0 | 1045 | 923 | 5.9 |
| 19 | ---- | ---- | 59.6 | 1075 | 1068 | 5.6 |
| 20 | 94.7 | ---- | 60.3 | 1160 | 1038 | 5.6 |
| 21 | ---- | ---- | 64.2 | 1243 | 1123 | 5.3 |
| 25 | 91.0 | 83.3 | 48.8 | 1640 | 1503 | 5.7 |
| 34 | 91.0 | 87.3 | 48.0 | 1878 | 1625 | 5.3 |
| 41 | 96.1 | 92.1 | ---- | ---- | ---- | 5.3 |

Table B-4. SUMMARY OF DATA FOR UNIT 4, FIRST PHASE

Oil Concentration (mixed systems) = 63 mg/L

| Day | TOC Removal Efficiency (%) Filtered | Settled | Sludge Volume Index | Suspended Solids (mg/L) Total | Volatile | pH |
|---|---|---|---|---|---|---|
| 0 | 93.6 | 81.6 | 88.0 | 1360 | 1203 | 7.1 |
| 1 | 93.2 | 85.0 | 104.5 | 1243 | 1037 | 6.4 |
| 2 | 93.2 | 84.1 | 78.6 | 1400 | 1115 | 6.2 |
| 3 | 96.5 | 89.2 | 68.2 | 1540 | 1290 | 6.1 |
| 4 | 95.6 | 92.5 | 62.7 | 1593 | 1303 | 5.9 |
| 5 | 98.5 | ---- | 60.0 | 1500 | 1323 | 5.9 |
| 6 | 96.9 | 91.8 | 50.0 | 1505 | ---- | 6.0 |
| 7 | 93.6 | 91.8 | 50.0 | 1500 | 1323 | 5.9 |
| 8 | 90.5 | ---- | 55.0 | 1358 | 1190 | 6.0 |
| 9 | 93.2 | ---- | 50.2 | 1393 | 1268 | 5.8 |
| 10 | 89.8 | 87.9 | 60.2 | 1161 | 1067 | 5.9 |
| 19 | ---- | ---- | 69.6 | 1148 | 1140 | 5.5 |
| 20 | 95.4 | ---- | 58.5 | 1195 | 1035 | 5.4 |
| 21 | ---- | ---- | 68.5 | 1275 | 1168 | 5.2 |
| 25 | 90.7 | 86.8 | 48.2 | 1555 | 1408 | 5.6 |
| 34 | 93.2 | 90.2 | 53.8 | 1900 | 1555 | 5.3 |
| 41 | 95.9 | 91.7 | ---- | ---- | ---- | 5.2 |

Table B-5. SUMMARY OF DATA FOR UNIT 5, FIRST PHASE

Oil Concentration (mixed system) = 100 mg/L

| Day | TOC Removal Efficiency (%) Filtered | Settled | Sludge Volume Index | Suspended Solids (mg/L) Total | Volatile | pH |
|---|---|---|---|---|---|---|
| 0 | 94.5 | 85.9 | 92.5 | 1080 | 983 | 6.9 |
| 1 | 93.9 | 83.3 | 118.8 | 1083 | 1017 | 6.4 |
| 2 | 93.2 | 77.3 | 82.7 | 1333 | 1093 | 6.2 |
| 3 | 96.3 | 91.5 | 72.2 | 1387 | 1223 | 6.1 |
| 4 | 96.3 | 93.9 | 70.2 | 1353 | 1083 | 5.9 |
| 5 | 98.7 | ---- | 64.6 | 1313 | 1220 | 6.0 |
| 6 | 97.0 | 92.0 | 50.9 | 1373 | ---- | 6.0 |
| 7 | 97.0 | 92.0 | 49.0 | 1430 | 1265 | 5.9 |
| 8 | 90.2 | ---- | 56.3 | 1245 | 1037 | 6.0 |
| 9 | 93.9 | ---- | 50.1 | 1396 | 1237 | 5.9 |
| 10 | 90.8 | 89.0 | 51.0 | 1178 | 1050 | 5.9 |
| 19 | ---- | ---- | 63.3 | 1103 | 1093 | 5.5 |
| 20 | 95.2 | ---- | 49.0 | 1120 | 1013 | 5.4 |
| 21 | ---- | ---- | 56.0 | 1248 | 1150 | 5.3 |
| 25 | 89.0 | 78.7 | 39.6 | 1513 | 1395 | 5.5 |
| 34 | 90.8 | 90.8 | 26.9 | 1855 | 1630 | 5.3 |
| 41 | 96.3 | 89.0 | ---- | ---- | ---- | 5.1 |

Table B-6. SUMMARY OF DATA FOR UNIT 1, SECOND PHASE

Oil Concentration (mixed system) = 0 mg/L

| Day | TOC Removal Efficiency (%) Filtered | Settled | Sludge Volume Index | Suspended Solids (mg/L) Total | Volatile | pH |
|---|---|---|---|---|---|---|
| 0 | 98.3 | 97.2 | 172.3 | 1995 | 1820 | 7.0 |
| 1 | 96.0 | 95.8 | 167.5 | 1860 | 1645 | 6.8 |
| 2 | 99.2 | 97.6 | 142.2 | 2115 | 1965 | 7.0 |
| 3 | 97.2 | 97.2 | 144.5 | 1800 | 1590 | 6.8 |
| 5 | 99.5 | 99.5 | 127.1 | 2050 | 1850 | 6.7 |
| 6 | 96.7 | 95.9 | 115.6 | 2250 | 1945 | 6.5 |
| 8 | 97.0 | 96.3 | 95.7 | 2250 | 1955 | 6.2 |
| 9 | 98.7 | 97.5 | 98.7 | 1770 | 1655 | 6.1 |
| 10 | 98.9 | 97.8 | 90.5 | 1825 | 1765 | 6.1 |
| 12 | 97.0 | 96.6 | 69.9 | 2005 | 1850 | 6.1 |
| 15 | 95.9 | 94.7 | 60.8 | 2640 | 2355 | 6.0 |

Table B-7. SUMMARY OF DATA FOR UNIT 2, SECOND PHASE

Oil Concentration (mixed system) = 63 mg/L

| Day | TOC Removal Efficiency (%) | | Sludge Volume Index | Suspended Solids (mg/L) | | pH |
|---|---|---|---|---|---|---|
| | Filtered | Settled | | Total | Volatile | |
| 0 | 98.5 | 97.2 | 170.2 | 2350 | 2130 | 6.9 |
| 1 | 97.5 | 94.0 | 155.0 | 2260 | 2030 | 6.5 |
| 2 | 99.0 | 92.0 | 109.5 | 2470 | 2240 | 6.3 |
| 3 | 98.3 | 97.0 | 134.0 | 1790 | 1540 | 6.2 |
| 5 | 99.0 | 95.8 | 86.5 | 1505 | 1310 | 6.2 |
| 6 | 98.3 | 87.5 | 84.8 | 1415 | 1335 | 6.1 |
| 8 | 92.3 | 92.8 | 71.3 | 1685 | 1520 | 5.9 |
| 9 | 97.5 | 92.6 | 56.0 | 1610 | 1560 | 6.1 |
| 10 | 98.9 | 95.5 | 70.7 | 2012 | 1875 | 5.9 |
| 12 | 95.3 | 94.8 | 60.0 | 2165 | 1995 | 5.9 |
| 15 | 96.5 | 90.5 | 54.5 | 2660 | 2445 | 5.7 |

Table B-8. SUMMARY OF DATA FOR UNIT 3, SECOND PHASE

Oil Concentration (mixed system) = 125 mg/L

| Day | TOC Removal Efficiency (%) | | Sludge Volume Index | Suspended Solids (mg/L) | | pH |
|---|---|---|---|---|---|---|
| | Filtered | Settled | | Total | Volatile | |
| 0 | 98.0 | 96.7 | 183.0 | 2185 | 1925 | 7.1 |
| 1 | 96.7 | 94.2 | 162.5 | 2400 | 2155 | 6.9 |
| 2 | 97.9 | 95.0 | 134.5 | 2380 | 2150 | 6.6 |
| 3 | 98.0 | 93.9 | 139.0 | 2010 | 1820 | 6.3 |
| 5 | 98.3 | 97.2 | 112.7 | 2130 | 1950 | 6.2 |
| 6 | 97.2 | 93.0 | 99.0 | 1970 | 1785 | 6.2 |
| 8 | 94.2 | 93.3 | 80.5 | 2050 | 1860 | 5.9 |
| 9 | 94.3 | 91.4 | 70.3 | 1925 | 1890 | 5.9 |
| 10 | 98.0 | 91.5 | 67.8 | 1770 | 1515 | 5.9 |
| 12 | 96.7 | 92.8 | 56.8 | 1935 | 1785 | 5.8 |
| 15 | 95.4 | 91.4 | 45.0 | 2115 | 1955 | 5.8 |

Table B-9. SUMMARY OF DATA FOR UNIT 4, SECOND PHASE

Oil Concentration (mixed system) = 313 mg/L

| Day | TOC Removal Efficiency (%) | | Sludge Volume Index | Suspended Solids (mg/L) | | pH |
|---|---|---|---|---|---|---|
| | Filtered | Settled | | Total | Volatile | |
| 0 | 99.4 | 97.7 | 144.0 | 2150 | 1895 | 7.3 |
| 1 | 97.2 | 88.9 | 152.5 | 2035 | 1800 | 7.0 |
| 2 | 98.7 | 88.3 | 129.2 | 1895 | 1760 | 7.0 |
| 3 | 98.0 | 87.7 | 94.2 | 2120 | 1445 | 6.6 |
| 5 | 97.7 | 85.9 | 104.2 | 1915 | 1735 | 6.3 |
| 6 | 96.2 | 80.2 | 94.4 | 1800 | 1655 | 6.2 |
| 8 | 95.8 | 87.0 | 97.3 | 2260 | 2140 | 5.9 |
| 9 | 95.4 | 90.2 | 87.5 | 1885 | 1820 | 5.9 |
| 10 | 95.6 | 84.5 | 85.2 | 2170 | 2070 | 5.8 |
| 12 | 94.3 | 93.0 | 77.7 | 2125 | 1970 | 5.9 |
| 15 | 95.1 | 92.8 | 64.4 | 2485 | 2280 | 5.8 |

Table B-10. SUMMARY OF DATA FOR UNIT 5, SECOND PHASE

Oil Concentration (mixed system) = 625 mg/L

| Day | TOC Removal Efficiency (%) Filtered | Settled | Sludge Volume Index | Suspended Solids (mg/L) Total | Volatile | pH |
|---|---|---|---|---|---|---|
| 0 | 98.1 | 90.6 | 173.2 | 1960 | 1780 | 7.1 |
| 1 | 97.2 | 96.7 | 152.3 | 1840 | 1610 | 6.9 |
| 2 | 97.7 | 89.0 | 128.2 | 1520 | 1430 | 6.7 |
| 3 | 97.9 | 84.2 | 125.5 | 1595 | 1420 | 6.2 |
| 5 | 96.5 | 88.5 | 119.8 | 1670 | 1530 | 6.2 |
| 6 | 93.5 | 80.9 | 93.5 | 1820 | 1620 | 6.2 |
| 8 | 96.5 | 89.5 | 81.5 | 1900 | 1880 | 5.9 |
| 9 | 94.6 | 89.8 | 78.2 | 2054 | 2000 | 5.9 |
| 10 | 92.3 | 89.3 | 74.8 | 2005 | 1845 | 5.9 |
| 12 | 94.7 | 91.1 | 63.7 | 2120 | 1980 | 6.0 |
| 15 | 94.8 | 88.0 | 75.2 | 2395 | 2230 | 5.9 |

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